Volume : 2 | Issue : 3 | March 2013 ISSN - 2250-1991

Research Paper Engineering

Transformer-Less High Gain Dc-Dc Converter For Fuel-Cell

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ABSTRACT

In this paper analysis and design of a new transformer-less high gain DC-DC converter for fuel cell DC converter is required. Typically to meet this requirement transformer based converters are used. With the consequent cost and size increase. As an alternative to the traditional solution the proposed converter provides a voltage gain of 5 in per unit without the need of a transformer. This contributes to a significant reduction in size and cost while maintaining high conversion efficiency. Moreover the proposed converter produces a split dc-link which can be independently controlled. This feature is ideal for bi-phase inverters to produce an AC output from a fuel-cell energy source. Converter analysis, and experimental results obtained from a 1kw,45v dc to 200v dc prototype are presented in this paper.

Keywords:

1. INTRODUCTION

As more countries ratify the Kyoto protocol aiming to reduce the emission of greenhouse gases produced by combustion of fossil fuels, along with rampaging high oil prices and concerns regarding the safety and disposal of by-products of nuclear generation has created the need of clean power generation systems. This presents a unique opportunity for the development and implementation of distributed generation.

Distributed generation normally uses environmentally friendly energy sources such as fuel cells, solar panels and micro hydroelectric plants to produce electric power. Among these fuel cells have been considered as the primary energy source for the next generation distributed power generation, since they are highly efficient,

modular and clean; however, as a draw back the DC voltage generated by a fuel cell stack varies widely, normally from 1 in per unit to 0.5 in per unit. Further the voltage produced by fuel cells is low in magnitude and therefore for applications where the output power is in the kilowatt range input voltages and currents can easily have the same order of magnitude. Thus they present challenging characteristics for the design of the power conditioning system required to interface the fuel cell to the utility grid or ac loads common in residential applications. By the fore mentioned reason a step-up DC-DC conversion stage is essential to generate an adequate input voltage for the DC-AC inverter stage (200V typically for a 120 V AC output). Normally the DC-DC converters used to accomplish this task take advantage of a high frequency transformer to provide the Voltage gain required. But the use of transformer based DC- DC converter has some dis-advantages such as increased size and cost.

Recently transformer-less converters have been proposed to reduce the size and cost of the power conversion units in applications where no electrical isolation is required [1-2]. But they lack of an adequate voltage gain, and sometimes require a dual input voltage. In this paper a new DC-DC converter topology is proposed to step up the fuel cell voltage and provide a stable dc-link for the DC-AC inverter. The proposed DC-DC power conversion unit consists of a hybrid connection of two two- level DC-DC converters. This produces an independently controllable dual voltage output. As it will be shown the use of the proposed topology along with a DC-AC inverter eliminates the need for a transformer to provide the required voltage gain. As a result, proposed topology has the following advantages:

1. Operates from a single input voltage
2. No transformer is required to achieve a voltage gain of 5 in per unit
3. If a single phase is connected at its output the system can generate 120V AC output from a 40V DC input source without the use of a transformer.

II. PROPOSED CONVERTER

The proposed DC-DC converter is shown in figure 1a. It uses as building blocks a two-level boost converter [3] and a two-level buck-boost converter. As can be seen from figure 1b, the inputs of the converters are connected in parallel and their outputs are in series, thus combining the voltage gains of each converter. The overall voltage gain of 5 per unit can be realized. The operation of the DC/DC converter can be explained by analyzing the two converters separately and then combining their input/output relationship .

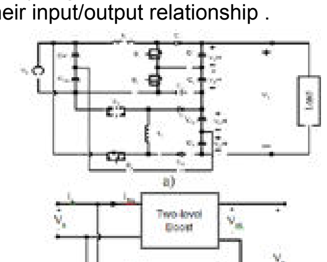

Figure 1 a) proposed high-gain dc-dc converter for fuel cell power systems b) connection block diagram

2.1 Two-level boost dc-dc converter

The operation of the two-level boost converter (figure 2) is detailed in [3] for single phase power factor correction applications. And its operation states are repeated here for completion. These states are distributed along the switching period and the duration of each state is determined by the duty cycle D. During one switching period the following switching state sequence is applied. If the voltage drop across diodes D1 and D2 is neglected to simplify the analysis, the equations describing the different states are:

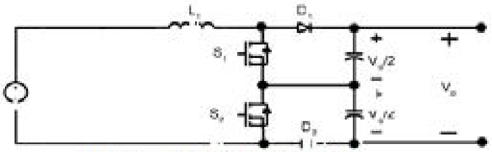

Figure 2 Two-level boost converter

1.Inductor charging state 1

Switches S1 and S2 are closed to charge inductor L1. During this switching state diodes D1 –D2 are reverse biased, as shown in figure 3a. During this stage the inductor voltage $V_L = V_s - 2R_{DS}I_L - R_L I_L$. The capacitor currents for this converter state are $I_{C1} = I_{C2} = -I_o$.

2. Energy transfer to capacitor C1 state

Switch S is opened and switch S remains closed. Diode D1 conducts and diode D2 remains reverse biased as shown in figure 3b. During this stage the energy stored in the inductor is delivered to the capacitor C1 Charging it. The inductor voltage in this case is $V_L = V_S - \frac{Vo}{2} - R_L I_L - R_{DS} I_L$

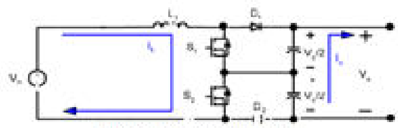

Figure 3a. Inductor charging state

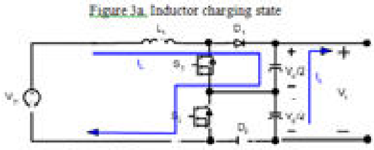

Figure 3b. Energy transfer to capacitor C_1

Figure 3c. Energy transfer to capacitor C_2

3. Inductor charge state 2

Again switches S and S are closed to charge the inductor L1 , and diode D1 –D2 are reverse biased, as shown in figure 3a. During this stage the inductor voltage is $V_L = V_s - 2R_{DS}I_L - R_L I_L$. The capacitor currents for this converter state are $I_{C1} = I_{C2} = -I_o$. .

4.Energy transfer to capacitor C1 state

Switch S is opened and switch S remains closed. Diode D1 conducts and diode D2 remains reverse biased as shown in figure 3c. During this stage the energy stored in the inductor is delivered to the capacitor C2 , and the voltage across the inductor is given by $V_L = V_s - \frac{Vo}{2} - R_L I_L - R_{DS} I_L$. For this converter state the capacitor currents are given by $I_{C1} = -I_o$ and $I_{C2} = I_L - I_o$. In steady state the switching pattern used for the converter operation is shown in the figure 4. From this figure and assuming that the inductor was charged during the previous switching cycle, state 2 is applied for a time given by $t_1 = \frac{(1-D)Ts}{4}$. Then the inductor is charged during a time t given by $t_2 = \frac{DTs}{2}$. Once the inductor is charged state4 is applied to the converter for a time $t_3 = \frac{(1-D)Ts}{4}$. After this the inductor is charged again for a time period $t_4 = \frac{DTs}{2}$. Once we finished charging the inductor, circuit will again enter the state 2 for a time $t_5 = \frac{(1-D)Ts}{4}$, to complete the one period cycle.

To obtain the voltage gain characteristic of the converter the inductor volt-second balance over one switching period is calculated. From that calculation the voltage gain characteristic of the converter is obtained to be:

$$V_o = V_s \frac{2}{(1-D)} \frac{1}{1 + \frac{4(Rds(1+D)+RL)}{(1-D)^2 R}}$$

From this analysis the inductor and input currents are calculated and are given by:

$$I_L = I_o \frac{2}{(1-D)}$$

$$I_S = I_L$$

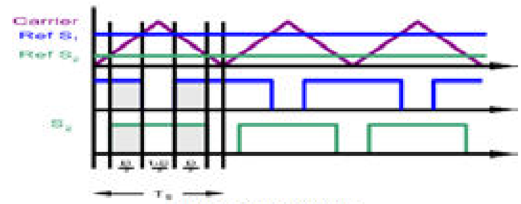

Figure 4. Switching pattern

Also from the analysis of the different switching states of the converter we can obtain the average equivalent circuit of the two level boost converter. Figure 5 shows the complete equivalent circuit including the losses in the inductor, MOSFET and diodes.

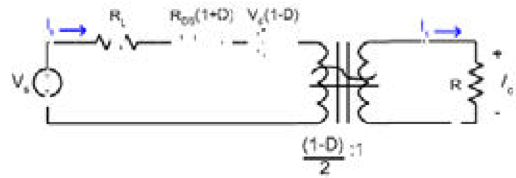

Figure 5. Average equivalent circuit

2.2.Two-level buck-boost dc-dc converter

The operation of the two-level buck-boost converter (figure 6) can be explained in the same manner as was done with the two-level boost converter. If we neglect the voltage drop in the diodes the equations for the switching states of the converter for one switching period are obtained as follows:

1.Inductor charge state1

Switches S1 and S2 are closed to charge inductor L. Diodes D1 –D2 are reverse biased, as shown in figure 6a. During this stage the inductor voltage is $V_L = V_s - 2R_{DS}I_L - R_L I_L$. The capacitor currents for this converter state are $I_{C1} = I_{C2} = -I_o$.

2.Energy transfer to capacitor C1 state

Switch S1 is opened and switch S2 remains closed. Diode D1 conducts and diode D2 remains reverse biased as shown in figure 6b. During this stage the energy stored in the inductor is delivered to the capacitor C1 by charging it to a voltage $V_{C1} = V_s + \frac{Vo}{2} - R_L I_L - R_{DS} I_L$. For this converter state the capacitor currents are given by $I_{C1} = I_L - I_o$ and $I_{C2} = -I_o$.

3.Inductor charge state 2

Again switches S1 and S2 are closed to charge the inductor L and diode D1 – D2 are reverse biased, as shown in figure 6a. During this stage the inductor voltage is $V_L = V_s - 2R_{DS}I_L - R_L I_L$. The capacitor currents for this converter state are $I_{C1} = I_{C2} = -I_o$.

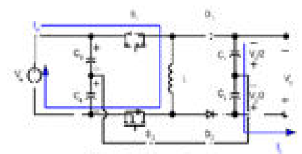

Figure 6a. Inductor charging state

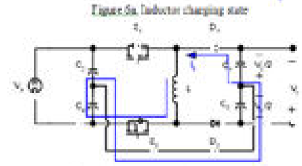

Figure 6b. Energy transfer to capacitor C_1

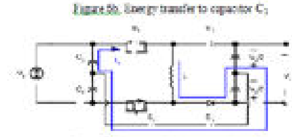

Figure 6c. Energy transfer to capacitor C_2

4.Energy transfer to capacitor C2 state

Switch S2 is opened and switch S1 remains closed. Diode D2 conducts and diode D1 remains reverse biased as shown in figure 6c. During this stage the energy stored in the inductor is delivered to the capacitor C2 charging it to a voltage $V_{C1} = V_L + \frac{Vs}{2} - R_L I_L - R_{DS} I_L$. For this converter state the capacitor currents are given by $i_{C1} = -I_o$ and $i_{C2} = I_L - I_o$.

The duration of each converter state can also be obtained using the method shown in figure 4. From this figure and assuming that the inductor is charged from the previous switching cycle state 2 is applied for a time given by $t_{S2} = \frac{(1-D)Ts}{4}$. Then the inductor is charged during the time t given by $t_c = \frac{DTs}{2}$. Once the inductor is charged, state 4 is applied to the converter for a time $t_{S4} = \frac{(1-D)Ts}{2}$. After this the inductor is charged again for a time period $t_c = \frac{DTs}{2}$. Once we finished charging the inductor, circuit will again enter the state 2 for a time $t_{S1} = \frac{(1-D)Ts}{4}$ to complete the one period cycle.

To obtain the voltage gain characteristic of the converter the inductor volt-second balance over one switching period is calculated. From that calculation the voltage gain characteristic of the converter is:

$$V_o = V_s \frac{(1+D)}{(1-D)} \frac{1}{1 + \frac{4(Rds\ (1+D) + RL\ )}{(1-D)^2 R}}$$

Using the same analysis the inductor and input currents are calculated and are given by:

$$I_L = I_o \frac{2}{(1-D)}$$

$$I_S = I_o \frac{(1+D)}{(1-D)}$$

In a similar fashion as in the case of the two level boost converter, we obtain the average equivalent circuit of the two level buck-boost converter from the switching state analysis. Figure 7 shows the resulting equivalent circuit which incorporates the losses due to the inductor, switches and diodes.

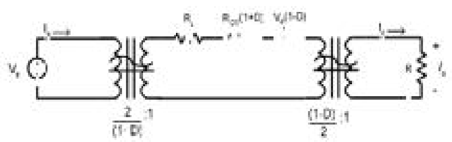

Figure 7. Average equivalent circuit

2.3.Proposed Four level dc-dc converter

As discussed in the previous sections, the proposed converter shown in figure 1 is realized by combining the two-level boost and buck-boost converters to obtain a higher voltage gain. The boost and buck-boost converters have their input terminals connected in parallel and their output terminals connected in series as shown in figure 1b. To obtain the total voltage gain and efficiency of the four level converter the output voltage and input currents of the individual converters are properly combined. From Figure 1b the output voltage of the four-level converter can be calculated by adding the output voltages of the two-level boost (1) and the two-level buck-boost converters (4).

$$V_o = V_{o,boost} + V_{o,buck-boost}$$

$$= V_s \left[\frac{2}{(1-D_1)} \frac{1}{1+\frac{4(Rds(1+D_1)+RL)}{(1-D_1)^2 R}} + \frac{(1+D_2)}{(1-D_2)} \frac{1}{1+\frac{4(Rds(1+D_2)+RL)}{(1-D_2)^2 R}} \right]$$

In the same manner the input current of the four-level converter is obtained by adding the input currents of the individual converters (3) and (6). The resulting expression is then given by:

$$I_{S,4-level} = I_o \left[\frac{2}{(1-D_1)} + \frac{(1+D_2)}{(1-D_2)} \right]$$

The efficiency of the four-level converter when inductors and semiconductor losses are included can be obtained by using the average equivalent circuits of figures 5 and 7. Using this method the efficiency of the converter is the given by:

$$\eta = \frac{P_o}{P_{in}} = \frac{V_o(Vs, D_1, D_2) I_o}{V_S I_S (I_o, D_1, D_2)} =$$

$$\frac{1}{\frac{2}{(1-D_1)} + \frac{(1+D_2)}{(1-D_1)}} \left(\frac{2}{(1-D_1)} \frac{1}{1+\frac{4(R_{DS}(D_1+1)+R_L)}{(1-D_1)^2 R}} + \frac{D_2+1}{1-D_2} \frac{1}{1+\frac{4(R_{DS}(D_2+1)+R_L+Vd(1-D_2))}{(1-D_2)^2 R}} \right)$$

where D1 and D2 are the two-level boost and two-level buck-boost duty cycles respectively. Plotting (7) and (9) for different inductor resistance versus load resistance ratios (R /R) the graphs shown in figure 8 are obtained. It can be L observed from figure 7 that although in theory this converter allows to get a voltage gain of 8p.u; a practical implementation of the converter considering losses in the inductor and semiconductors can produce a maximum voltage gain of 6 p.u if the converter efficiency is to be kept above 80%.

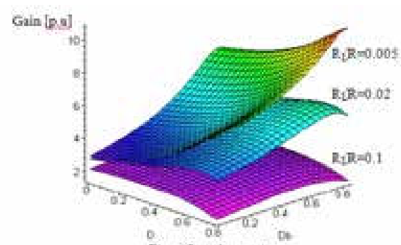

Figure 8a. voltage gain

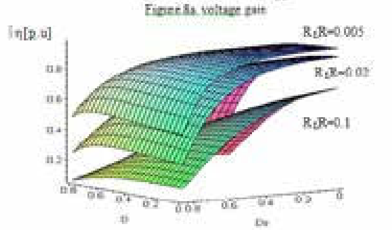

Figure 8b. estimated efficiency

III. DESIGN EXAMPLE

A design example of a 45Vdc to 200 Vdc, 1 kW DC-DC converter is outlined in this section. To generate 200 V dc at the converter output the total voltage gain required is 5, so it is needed that each stage supplies a voltage gain of 2.25p.u. By using equation (1), and considering that the switch on resistance as 80 mΩ and inductor resistance as 0.5Ω, we obtain that the boost converter has to be operated with a duty cycle D1= 0.32. Similarly by using equation (4) we obtain that the duty cycle of the buck-boost converter to be D2 = 0.54. To calculate the value of the inductor for the two level boost

$$L = \frac{R(1-D)D}{8f_s}$$

Designing the converter to operate in continuous conduction in a load range from 10% to 100% at a switching frequency of 50 kHz we obtain that a 218 μH inductor is needed. In the case of the inductor for the two level buck-boost converter from figures 4 and 6 we can obtain an equation(11)

$$L = \frac{R(1-D)D}{4(1+D)f_s}$$

From (11) and designing for the same switching frequency and load range as the boost converter we obtain that the inductor required has a value of 248 μH. For the design of the values of capacitors C1 – C4 equation (12) can be used.

$$C = \frac{V_o D}{4R\Delta V f_s}$$

For an output voltage ripple of less than 1% we obtain that the capacitor values are 100μ F. The current and voltage for the switches in the two level boost converter can be obtained from (2) and the output voltage of the stage. Thus switch current is 7.35 A and the switch voltage stress of the boost stage is 250 V. In the case of the switches for the two level buck boost converter the switch current can be calculated from (5) and it results to be 10.6A.The switch voltage stress is two times the output voltage of the buck-boost stage, i.e. 250 V.

IV.EXPERIMENTAL RESULTS

A laboratory prototype of the proposed converter was built to verify the analysis and simulations. The converter was implemented using four IRFPS40N60K MOSFETs and four DSEI 12-20 diodes. The inductors were designed and wound on toroidal iron powder cores and their value was measured to be 250 H with a series resistance of 0.5 Ohms. Figure 9 shows experimental waveforms for the converter operating from a 45 V dc input source. The output voltage of the converter is measured to be 204 V and the output power is 0.5 kW. In the figure the top traces correspond to the voltage across the output capacitors of each converter block, i.e. C 1/C2 and C 3/C4 . As can be observed from the figure the output voltage of the boost stage is 110 V and the voltage of the buck-boost stage is 94 V. This confirms that each converter block is providing a voltage gain of 2.44 p.u. and 2.09 p.u. respectively. The voltage gains of the converters are set at different values in order to maintain the inductor rms current in each converter at a similar level. This in turn has the effect of splitting the losses evenly between the two stages. The traces in figure 10 shows the inductor current waveforms measured at the output of the current sensors. The scaling factor of the sensors is 2.84 A/V. As can be seen from the figure the currents in the two inductors are kept at the same value, 7.24 A in this case. The total input current of the converter is measured to be 14.6 A. Figure 11 shows the voltage across switches S1 and S3. As can be observed from this figure the voltage stress of the switches is 2.5 times the output voltage of the converter.

Figure 12 shows the converter efficiency measured from the prototype for different output loads. As can be seen from the figure the efficiency of the converter is above 75 % for light loads and as the load increases it improves to values above 80%.

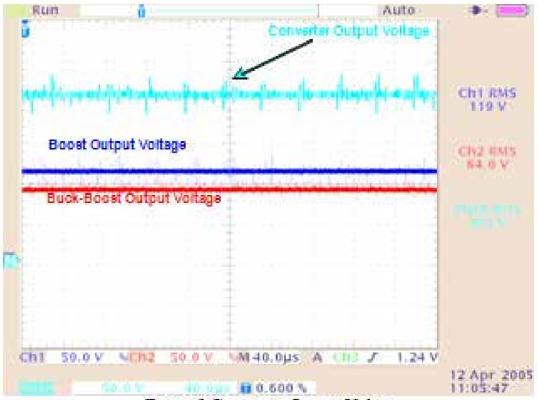

Figure 9 Converter Output Voltage

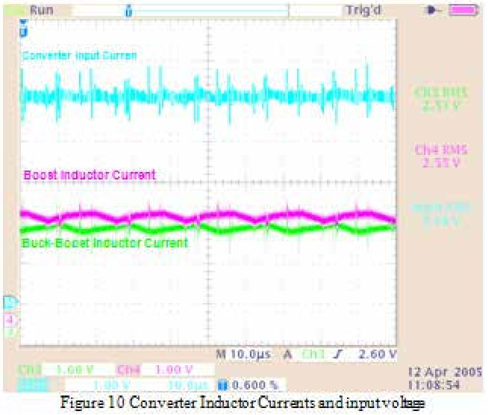

Figure 10 Converter Inductor Currents and input voltage

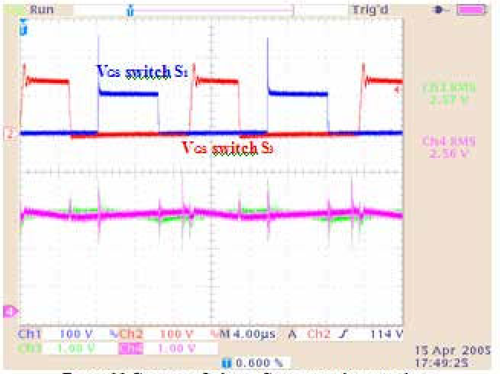

Figure 11 Converter Inductor Currents and input voltage

VI.CONVERTEREFFICIENCY IMPROVEMENT

As shown in figure 12 the efficiency measured from the prototype converter is in the range of 80%. For higher efficiency the inductor losses need to be reduced by optimizing the design of the magnetic core and by limiting the resistive losses of the magnetic wire. Further improvement inefficiency can be obtained by replacing diodes D1 – D4 by using MOSFET synchronous rectifiers. Figure 13 shows the converter topology a for higher efficiency design .

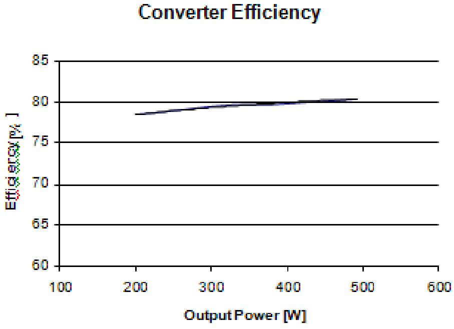

Figure 12 Measured converter efficiency

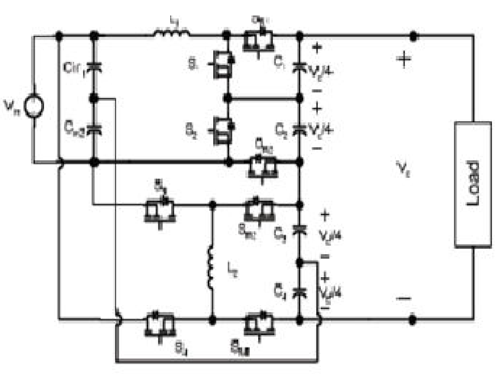

Figure 13 Synchronous rectifier approach

The efficiency of the modified converter can now be calculated using the same analytical method used to obtain the efficiency of the original converter using diodes. From the analysis the efficiency of the converter when synchronous rectifiers are used is derived to be as shown in equation (14)

$$\eta = \frac{P_o}{P_{in}} = \frac{V_o(Vs, D_1, D_2) I_o}{V_S I_S(I_o, D_1, D_2)} = \frac{1}{\frac{2}{(1-D_1)} + \frac{(1+D_2)}{(1-D_1)}} \left(\frac{2}{(1-D_1)} \frac{1}{1 + \frac{4(2R_{DS}+R_L)}{(1-D_1)^2 R}} + \frac{D_2+1}{1-D_2} \frac{1}{1 + \frac{4(2R_{DS}+R_L+Vd(1-D_2))}{(1-D_2)^2 R}} \right)$$

The efficiency of the converter when using diodes and synchronous rectifiers can be compared from the plots shown in figure 14. This figure shows the calculated efficiency of the converter for different duty cycles calculated from equations (9) and (13). For example if the duty cycles of the boost and buck-boost converters are set at the values calculated in the design example, D1 = 0.32 and D2 =0.54. The efficiency when using diodes is 80%, whereas if synchronous rectifiers are used the efficiency of the converter is calculated to be 85.3 %.That is the efficiency of the DC/DC converter improves by 5% if synchronous rectifiers are used. Further if the losses in the inductor can be reduced and the inductor resistance to load resistance ratio can be improved from 0.01 in the experimental prototype to 0.007 the efficiency of the converter can be improved up to 91%.

VII. CONCLUSIONS

In this paper a high-gain transformer-less DC-DC converter suitable for fuel-cell applications has been presented. The proposed converter employs a two level boost and a two level buck-boost converter in cascade to obtain a high voltage gain. The fact that this converter does not require a transformer to obtain the voltage gain needed to supply a single phase inverter can significantly reduce the cost and size of the system. The proposed converter operation has been shown to result in low input current ripple, which can contribute to low EMI. Experimental results demonstrate the feasibility of the proposed DC-DC converter. An show that a voltage gain of 5 p.u is obtainable.

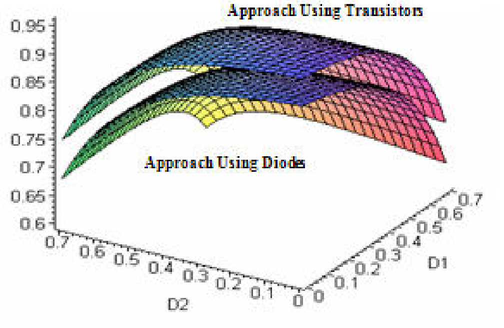

Figure 14 Efficiency improvement with synchronous rectifiers

REFERENCES

[1[N.Kasa, T. Iida, H. Iwamoto, "An Inverter using buck-boost Type Chopper Circuits For Popular Small-sacle Photovoltaic Power System," Industrial Electronics Society, 1999. IECON '99 Proceedings. The 25th Annual Conference of the IEEE , Volume: 1 , 29 Nov.-3 Dec. 1999, pp.185 - 190 vol.1 | [2] Y. Xue, L. Chang, S.B. Kjær, J. Bordonau, T. Shimizu, " Topologies of Single-Phase Inverters for small Distributed Power Generators : An Overview ",Power Electronics, IEEE Transactions on , volume: 19 , Issue: 5 , Sept. 2004 pp. 1305 - 1314 | [3] M.T. Zhang, Y. Jiang, F.C. Lee, M.M. Jovanovic, "Single-phase three level boost power factor correction converter", Applied Power Electronics Conference and Exposition, 1995. APEC '95.,Conference Proceedings 1995., Tenth Annual, Issue 0, 5-9 March 1995 Page(s):434 - 439 vol.1 | [4] M. Pagano, L. Piegari, "Electrical networks fed by fuel-cells for uninterruptible electrical supply," Proceedings of the ISIE, May 2002,02, pp 309-314 vol.1 | [6] W. Choi; P. Enjeti; J.W. Howze;" Fuel cell powered UPS systems: design considerations"; Power Electronics Specialist, 2003. PESC '03. IEEE 34th Annual Conference on, Volume: 1, 15-19 June 2003 pp.:385 – 390 vol.1 | [7] Y. Song; P. Enjeti;" A High Frequency Link Direct DC-AC Converter for Residential Fuel Cell Power Systems"; Power Electronics Specialist, 2004. PESC'04, IEEE 35th Annual Conference on, Volume: 2, 20- 25 June 2004, pp 4755 – 4761 | [8] F.L Luo;"Double-output Luo converters, an advanced voltage-lift technique", Electric Power Applications, IEE Proceedings- , Volume: 147, Issue: 6, Nov. 2000 pp 469-485 | [9] Center for Sustainable Systems, "U.S. Renewable Energy", Center for Sustainable Systems website, http://css.snre.umich.edu/css_doc/CSS03-12.pdf |